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Cyanobacterial productivity, variations in the organic carbon, and facies of the Indidura Formation (Cenomanian-Turonian), Northeastern Mexico.

Productividad cianobacteriana, variaciones del carbono orgánico y facies de la Formación Indidura (Cenomaniano-Turoniano), noreste de México

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Abstract

Rock sequences of Cenomanian-Turonian age commonly assigned to the Indidura Formation in northeastern Mexico (Coahuila State) show distinct facies indicative of significant spatial variability over the carbonate platform. Three stratigraphic sections where selected to characterize these differences.

Las Delicias section (stratotype) is composed of 10-30 cm thick beds of very-pale orange biocalcirudites, without internal primary structures. Allochems consist of abundant echinoderms, pelecypods, ammonites, and fewer planktonic foraminifera. Total carbonate ($CaCO_3$) varies between 48% and 94%, and total organic carbon (TOC) between 0.7 % and 1.5 %.

La Casita Canyon section, southeast of Las Delicias, consists of 3-30 cm thick interbeds of pale yellowish brown biocalcilutites and olive gray shales. Hand specimens show no apparent depositional internal structures, whereas abundant bioturbation appears in thin sections. Allochems consist of sparse fragments of planktonic foraminifera and radiolaria concentrated in burrows. Total carbonate ($CaCO_3$) varies between 0.8 % and 59.3 %, whereas TOC fluctuates between 0.17 % and 5.8 %.

In contrast, the Sierra de Parras section, south of Las Delicias and west of La Casita, includes a sequence with well defined rhythms. They consist of 8-200 cm thick beds of light olive gray and brownish black, to olive black shales; and 5-100 cm thick marly biocalcilutites. Both facies exhibit similar internal structures arranged in nearly even-parallel "varve-like" dual lamination (<3 mm thick). Microscopically, they include few planktonic foraminifera scattered in the dark laminae. Epifaunal remains include only sporadic pelecypods (*Inoceramus*). Total carbonate ($CaCO_3$) content varies from 43% to 78.3%, while TOC is relatively high between 7.3% and 24.3%, more often higher than 20%. Microfacies in the Parras area reveal compositional differences in the laminae associated with varying abundance of microspheres or "micro-ooids" that we attribute to be of cyanobacterial origin. Laminae developed from fluctuating cycles of calcareous cyanobacteria blooms, which remained dominant throughout the sequence. $C_{organic}$–rich black shales and limestones of the Parras region further document unique paleoceanographic conditions, which were also characterized by strong dysoxic/anoxic bottom conditions and rhythmical production of cyanobacteria. These conditions contrast sharply with prevailing paleoenvironments recorded at Las Delicias and La Casita where benthic epifauna, planktonic and nektonic organisms were able to thrive. Assuming that these facies are coeval, microfacies and TOC analyses of these rocks further demonstrate distinct spatial differences between these areas.

Keywords: cyanobacteria, Cenomanian/Turonian, organic-rich sediments, Mexico, laminae, anoxia.

Resumen

Las rocas de edad Cenomaniano-Turoniano normalmente asignadas a la Formación de Indidura en México nororiental (Estado de Coahuila) contienen facies distintivas que son indicativas de una variabilidad espacial importante a través de la plataforma de carbonatos. Se han seleccionado tres secciones estratigráficas para probar si estas diferencias existen.

La sección de Las Delicias (estratotipo) esta caracterizada por capas naranja claro de biocalciruditas (10-30 centímetros de espesor). Las estructuras internas primarias están ausentes. Los aloquímicos consisten esencialmente en asociaciones ricas en fósiles de equinodermos, pelecípodos, así como amonitas y foraminíferos planctónicos. El contenido de carbonato total ($CaCO_3$) varía entre 48% y 94%, y el contenido de carbono total orgánico (TOC) entre 0,7% y 1,5%.

La sección del Cañón La Casita, está al sureste de Las Delicias. Esta consiste en capas café claro amarillento de biocalcilutitas y lutitas laminadas verde oliva a grises con espesores de 3 a 30 cm. No se observa ninguna estructura interna deposicional; en las secciones delgadas se observa claramente abundante bioturbación. Los aloquímicos esencialmente son fragmentos esparcidos de foraminíferos planctónicos y radiolarios concentrados en madrigueras. El carbonato total ($CaCo_3$) varía entre el 0,8% y 59,3%, mientras que el TOC varia entre el 0,17% y 5,8%.

En contraste con estas sucesiones pobremente laminadas, en la Sierra de Parras, al sur de La Delicias y al oeste de la Casita, la sucesión se presenta como intercalaciones rítmicas de lutitas laminadas grisverdosas y negroparduzcas con espesores de 8 a 200 cm y biocalcilutitas margosas de 5 a 100 cm de espesor. Ambas facies exhiben estructuras internas similares organizadas en forma de laminillas duales paralelas “varvas” de < 3 mm de espesor, que contienen escasos foraminíferos planctónicos esparcidos en las laminillas oscuras. No se hay restos de epifauna, salvo esporádicos pelecípodos (Inocerámidos). El contenido de carbonato total ($CaCO_3$) varía entre 43% y 78,3%, mientras que el contenido de TOC es relativamente alto con valores entre 7,3% y 24,3%, consistentemente superiores a 20%.

La observación, de las laminillas presentes en las facies del área de Parras, muestra que sus diferencias composicionales están asociadas a la variabilidad en la abundancia de esferas microscópicas o “micro-oolitos.” Estas estructuras son interpretadas como de un posible origen cianobacteriano y se entienden como ciclos que representan eventos de florecimientos de cianobacterias, las cuales permanecieron dominantes a lo largo de la sucesión. Aún más, las lutitas laminadas y biocalcilutitas negras y ricas en TOC de la región de Parras documentan unas condiciones paleoceanográficas únicas, las cuales estaban caracterizadas por aguas oceánicas relativamente pobres en oxígeno.

La distribución de la epifauna y las variaciones de carbón/carbonato en la región de Parras, sugieren que en los fondos de acumulación hubo fuertes eventos rítmicos de disoxia/anoxia. Esto contrasta claramente con los sedimentos de las áreas de Las Delicias y de La Casita, en las que se documentan condiciones del fondo diferentes, donde la epifauna bentónica y la fauna planctónica y nectónica pudieron proliferar. Asumiendo que estas facies son coetáneas, los análisis de microfacies y de TOC de estas rocas demuestran aún más las diferencias entre estas áreas.

Palabras clave: cianobacterias, Cenomaniano/Turoniano, sedimentos ricos en materia orgánica, México, anoxia.

1. Introduction

Evolution of Cretaceous oceans includes several episodes of Oceanic Anoxic Events (OAEs) that are particularly well recorded in $C_{organic}$–rich sediments around the Tethys from the Early Jurassic (Borrego *et al*., 1996) up to the Cenomanian/Turonian (C/T) boundary time (Lamolda, 1978; Lamolda and Mao, 1999). Geochemical studies of Cretaceous sediments around the Tethyan realm led to further quantitative interpretations of the paleoclimatic and paleoceanographic conditions at that time (Schlanger and Jenkyns, 1976; Jenkyns, 1980; Arthur and Premoli-Silva 1982; Arthur *et al.,* 1990). Oceanic Anoxic Events (OAEs) are characterized by extensive preservation of organic carbon associated with widespread accumulation of “black shales” (Jenkyns, 1980; Bralower *et al.*, 2002). The C/T interval is not only widely associated with deposition of black shales during the Oceanic Anoxic Event designated as OAE-2, also known as the “Bonarelli Event”, but it is also characterized by the extinction of numerous taxa (Harries and Kauffman, 1990).

As recorded elsewhere, sediments deposited in the shallow epicontinental seas that extended over northeastern Mexico also indicate that general conditions of sedimentation favored the preservation of organic carbon from the Jurassic to the Cretaceous. As for plausible causes of such unusual preservation of $C_{organic}$–rich compounds in the lower Aptian (OAE 1b) of the La Peña Formation of northeastern Mexico, Barragán (2000) and Barragán and Maurrasse (2000) proposed that oxygen depletion caused an enhancement of the oxygen minimum zone due to an increase in oceanic water temperature related to tectono-volcanic effects associated with the Pacific super-plume events, which produced excess heat flux at that time. Their interpretation is compatible with Tatsumi *et al.'s,* (1998) inference that elevated temperatures, as well as changes in ocean chemistry, oceanic circulation and sea level, were all factors that played a major role in oxygen

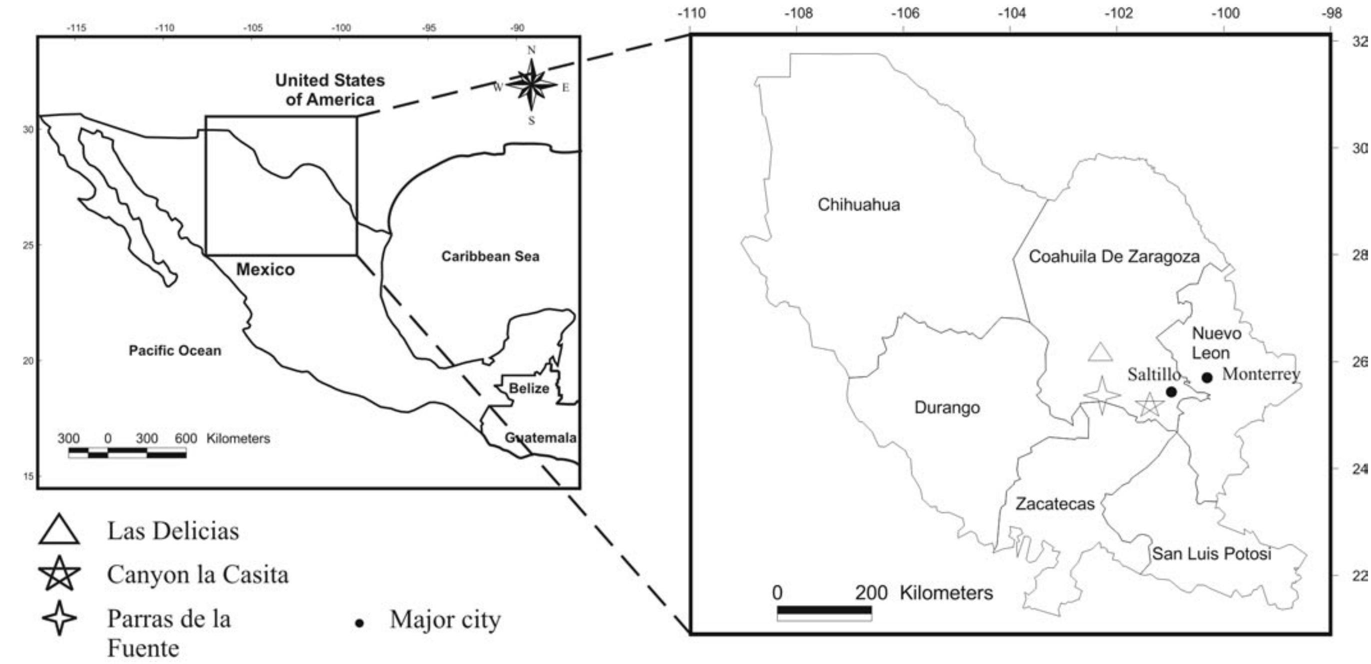

Fig. 1.- Map of Mexico showing the location of the region referred to as northeastern Mexico. Close up of the region with localization of the three stratigraphic sections.

Fig. 1.- Mapa de México mostrando la localización de la región referida en el noreste de México. Detalle de la región, con la ubicación de las tres secciones estratigráficas.

depletion events during the mid-Cretaceous hypoxic conditions. Hence, the net result of the superplume events associated with the lower Aptian (OAE 1b) is distinguished by a general enhancement of the oxygen minimum level in the Tethyan realm and epicontinental seas where there was an increase in TOC, (up to 20+%), in the La Peña Formation, for instance. The patterns of occurrence/ disappearance of the benthic fauna (Barragán, 2000; Barragán and Maurrasse, 2000) further corroborate the anoxic conditions coincident with (OAE 1b).

In the present work we discuss the different facies commonly assigned to the Indidura Formation, and focus special attention to sediments in the Parras Mountains, a rock sequence from northeastern Mexico (Fig. 1), which covers the C/T boundary, a time also known to include a significant Oceanic Anoxic Event. With still many unanswered questions concerning the C_{org}-rich Cretaceous sediments of that time, the present work presents geochemical and petrographic analyses that will shed further light on our understanding of the sedimentary cycles and C_{org}-rich events of the Indidura Formation (Duque-Botero and Maurrasse, 2002a,b). We also present evidence of the role played by cyanobacteria in the biological-sedimentological processes that were significant in the formation of C_{org}-rich deposits in northeastern Mexico, and perhaps similar processes may be applicable elsewhere in the geological record.

2. Physical Stratigraphy of the Study Area

It has long been recognized that Cretaceous rocks of northeastern Mexico indicate that complex and lasting shallow-platform environments were established over the area since at least the Valanginian (Imlay, 1936). The general stratigraphy (Fig. 2) includes the following predominately calcareous units: The Taraises Formation composed of calcareous shales and fossiliferous limestones with intervals rich in mollusks (Imlay, 1936). The type locality may include Berriasian to lower Hauterivian strata (Humphrey and Diaz, 2003). The Capulin? Formation (Humphrey and Diaz, 2003), formerly referred to as Las Vigas Formation by Imlay (1936) following the work of Burrows (1910). The formation is composed "principally of fine- to medium-grained brown to yellowish brown calcareous sandstones and siliceous, shaly somewhat sandy limestones" (Humphrey and Diaz, 2003). According to Humphrey and Diaz (2003) the formation does not include diagnostic fossil to allow its time stratigraphic correlation. Nonetheless, based on its stratigraphic position, they suggest that it may lie between the late Hauterivian and the early Barremian. The Cupido Formation (Imlay, 1937; Humphrey, 1949), overlies the Capulin? Formation, and consists of dark gray to black limestones with rudists assigned to the Barremian. Deeper-water limestones and marls of Barremian to Aptian ages occur westward of the platform, and are commonly referred to as the Tamaulipas Formation (Ross, 1981). The La Peña Formation (Imlay, 1936, sensu Humphrey, 1949) overlies the Cupido limestones and comprises marl/shale facies with ammonites of Aptian age. They are succeeded by gray Aurora limestones (Imlay, 1940), grading into thinly-bedded, shaly limestones, gray shales and numerous chert stringers described as the Cuesta del Cura Limestone (Imlay, 1936, 1937) of late Albian age. The latter is overlain by the sedimentary sequence of the Indidura Formation, named and described by Kelly (1936) in the Las Delicias area of western Coahuila State.

Kelly (1936, p. 1028-1029) defined the Indidura Formation as composed in its lower part of "…imperfectly consolidated buff shales containing many crystals of selenite. A thin transitional zone of intercalated platy limestone and shale is included with the Indidura. The highest beds observed are imperfectly stratified buff shales containing numerous veinlets of selenite"; he further added that "…the formation is about 100 feet thick and is divisible in three parts. The lower and upper divisions include the shale beds already mentioned. The middle division consists of interbedded rubbly, gray, pink and red argillaceous limestones, platy limestones and calcareous shale. Some fossils were collected from the lower division, but they are more numerous in the middle, where there are some fossiliferous horizons. Echinoidea, pelecypoda, and cephalopoda are the best represented classes". Shortly thereafter, Imlay (1936) further expanded the name Indidura Formation to rock sequences in the rest of the Sierra Madre Oriental. Jones (1938) later reported the fauna as of transitional character, and of Cenomanian-Turonian age.

According to Imlay (1936), the Indidura Formation of the Parras area is in gradational contact with the Cuesta del Cura Formation, and is marked by the appearance of gray shale beds. In that area, the Indidura Formation was estimated to reach a maximum thickness of 1,900 ft (578 m), and consists of interbedded black and gray shale (up to 75 cm), with black to yellowish limestone (up to 35 cm). The lowermost part of the Indidura Formation consists of an estimated 243 to 274 meters of powdery, and in places laminated, gray calcareous shales, with thin intercalations of dark gray limestones beds that are either lenticular or continuous. The middle part consists of an estimated 121 to 152 meters of finely laminated "salt and pepper" shales that alternate, particularly in the lower 20 meters, with sandy shales that contain lenses of brown selenite up to 80 cm thick. The uppermost part consists of 152 meters of platy, gray calcareous shales and brown to light-gray shaly limestones with some intercalations of sandy shales that contain abundant selenite crystals. The

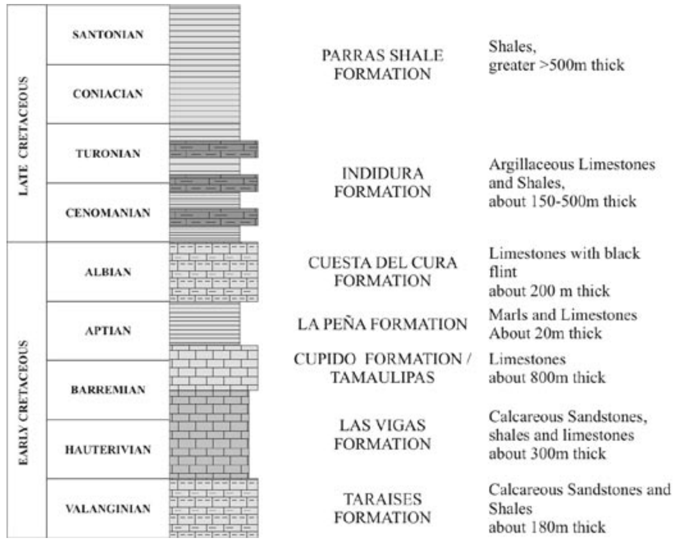

Fig. 2.- Generalized stratigraphic section (not drawn to scale due to lateral variations in thickness) of northeastern Mexico showing the main units present in the western part of the Sierra de Parras; data compiled from Imlay (1936, 1937).

Fig. 2.- Perfil estratigráfico general del noreste de México mostrando las unidades principales en la parte oeste de la Sierra de Parras (no dibujado a escala, debido a las variaciones laterales en la potencia); datos compilados de Imlay (1936, 1937).

uppermost section of the rocks assigned to the Indidura Formation in the Sierra de Parras area is in sharp contact with the overlying Parras Formation. Based on its fossil content, Imlay (1936, 1937) assigned a Cenomanian-Turonian age to the Indidura Formation in the western part of the Sierras de Parras, and suggested that it might include Lower Coniacian. The Parras Shale (Imlay 1936,1937) is composed of black calcareous shale with interbedded dark gray siltstone, its age is uncertain due to the scarcity of diagnostic fossils.

3. Samples and Laboratory Methods

Samples of rock sequences attributed to the Indidura Formation were collected from three sections in the Sierra Madre Oriental, NE Mexico. These sites are found 1) in the Sierra de Las Delicias "the stratotype area" (Kelly, 1936); 2) in the canyon la Casita (Imlay 1936); and 3) near the town of Parras de la Fuente, Coahuila (Duque-Botero and Maurrasse, 2002b), see Figure 1 for localities. Thin sections where prepared, described, and characterized with the help of a polarized light microscope using Folk's (1980) classification scheme. Polished rock slabs and thin sections where acid etched following the technique described by Folk (1993), and were analyzed for imaging and semiquantitave chemical analysis with a SEM JSM-5900-LV. Samples were later described for

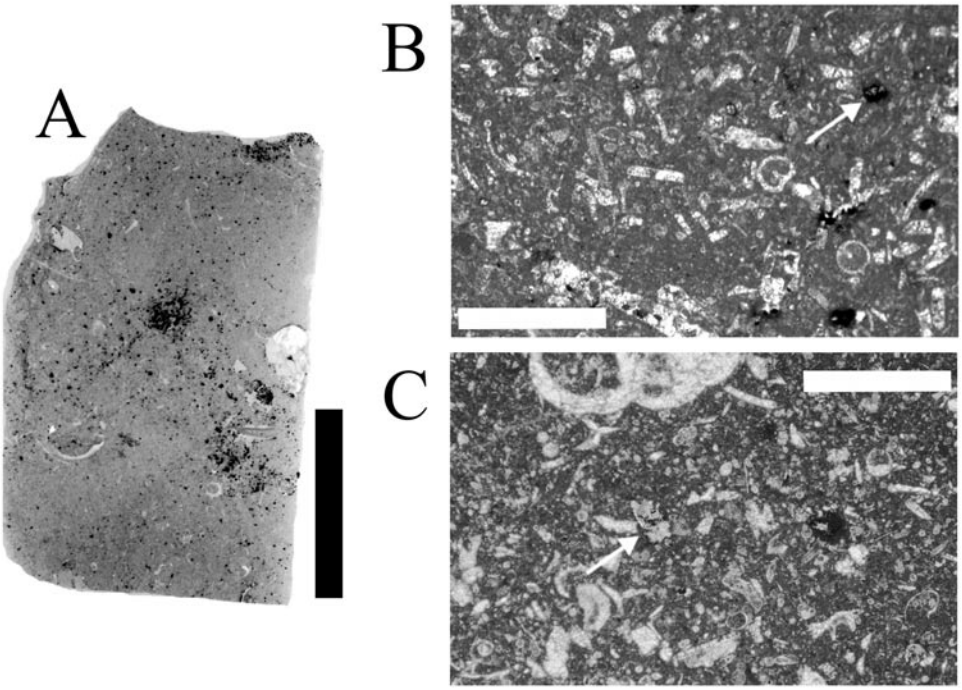

Fig. 3.- A) Petrographic thin section from Las Delicias: showing no primary sedimentary structures. Abundant fragments of echinoderms, gastropods and pelecypods molds are observed (scale bar = 1.5 cm). B and C) Biocalcirudite microphotographs (plain light). Microsparite is the predominant cement, recrystallized echinoderm and gastropod molds make up most of the rock. Arrow in (B) points to pyrite grains, in (C) to glauconite grains (B and C scale bar = 500 µm).

Fig. 3.- A) Lámina delgada de una muestra de Las Delicias, donde no se observan estructuras sedimentarias primarias; con abundantes fragmentos de equinodermos, gasterópodos y moldes de pelecípodos (escala gráfica = 1,5 cm). B y C) Fotomicrografías de biocalcilutita (luz natural). El cemento principal es la microesparita. Moldes recristalizados de equinodermos y gasterópodos constituyen casi la totalidad de la roca. La flecha en B) indica granos de pirita, en C) indica granos de glauconita. (Escala gráfica en B y C = 500 µm).

intrinsic sedimentological characteristics and microstructures that are not observable with standard petrographic microscopes. Analyses for carbon/carbonate content were conducted on fresh samples using a LECO CR-412 analyzer, and results are presented as carbon percent C (%) for dry weight bulk sample.

4. Data and Results

4.1. Sedimentary and petrographic descriptions

4.1.1. Las Delicias (type locality area)

As observed at the type locality selected by Kelly (1936), at the field scale the Indidura Formation is composed of interbeds of very-pale orange (10YR8/2) biocalcirudites and marls 10-30 cm thick. Macrofossils include abundant ammonites, echinoderms and pelecypods. The beds are rather stuctureless, both at the macroscopic as well as the microscopic scales. Total obliteration of kinematically produced aqueous primary structures is consistent with high aerobic levels in the water column and within the upper part of the sedimentary column as attested by the rich epifauna (Brenchley and Harper, 1998). Petrographically, calcite makes up an average of 80% of the main constituent with values as high as 93%. Other minor constituents include pyrite cubes (<8%), and rounded glauconite grains. Microsparite is the chief cement with less than 10% of the total rock groundmass recrystallized into sparry calcite. Benthic and planktonic foraminifera comprise no more than 5% of the total fossil assemblage. Most macrofossils and microfossils are filled with recrystallized sparry calcite (Fig. 3 C).

4.1.2. La Casita Canyon

Rocks assigned to the Indidura Formation at the La Casita canyon are composed of 3 to 30 cm-thick interbeds of pale yellowish brown (10YR6/2) biocalcilutites and olive gray (5Y3/2) shales. Macroscopically the beds exhibit no internal lamination. Closer observation reveals extensive burrowing (Fig. 4 A) that may have obliterated any primary subaqueous structures that could have been associated with sedimentation. Although no benthic fossils were found, such biogenically induced isotropic fabric is consistent with aerobic bottom waters (Brenchley and Harper, 1998) that allowed epibenthos and inbenthos colonization with subsequent destruction of initial

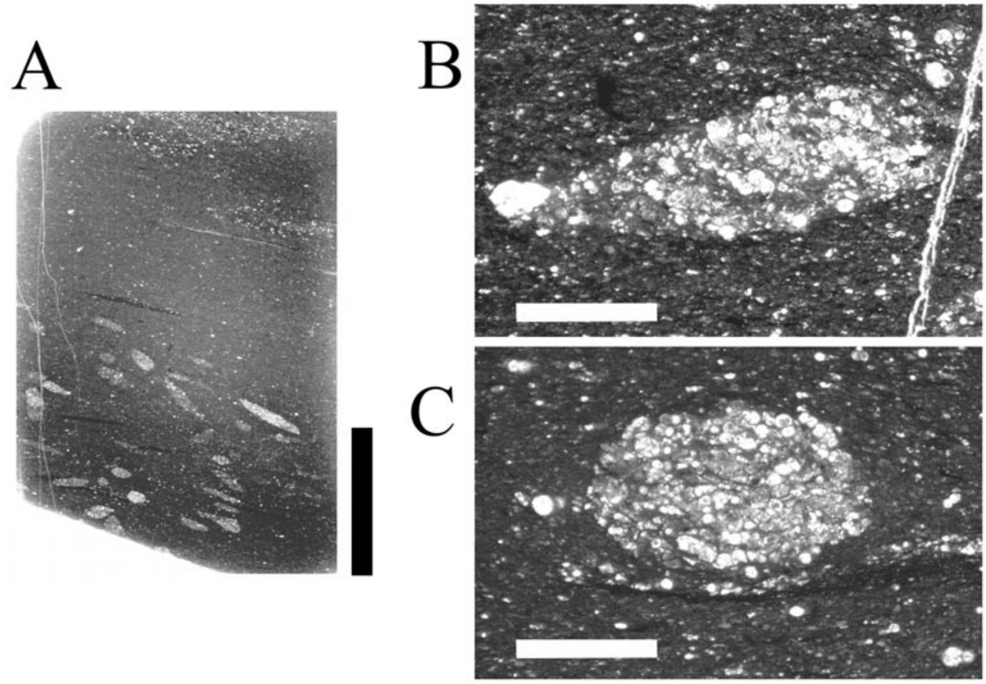

Fig. 4.- A) Petrographic thin section from La Casita: no laminations or original internal features are observed, small burrows < 2 mm in diameter are seen (scale bar = 1.5 cm). B and C) Biocalcilutite microphotographs (plain light). Filled burrows contain planktonic foraminifera and few radiolarians. Some microfossils are scattered outside burrows (B and C scale bar = 500 μm).

Fig. 4.- A) Lámina delgada de una muestra de La Casita: se observa la ausencia de laminaciones o características internas originales, y la presencia de madrigueras de pequeño diámetro < 2 mm (escala gráfica = 1,5 cm). B y C) Fotomicrografías de biocalcilutita (luz natural). Las madrigueras contienen foraminíferos planctónicos y algunos radiolarios. Algunos microfósiles se encuentran esparcidos fuera de las madrigueras. (Escala gráfica en B y C = 500 μm)

laminae. Petrographically, clay minerals are the dominant constituents, with an average of 68% and a maximum of 98%. Carbonate components can reach values up to 50% of the rock, as recrystallized foraminifera and calcitized radiolarians, which are concentrated in burrow-filling structures (Fig. 4 B, C), and micrite is the main cement.

4.1.3. Parras de la Fuente area

At a locality west of the town of Parras de la Fuente, in the northwestern flank of the Sierra del Parras (GPS coordinates; 25° 26' 17.9" N; 102° 12' 54.7" W); the sequence referred to as the Indidura Formation consists of interbedded light olive gray (5Y6/1) and brownish black to olive black (5YR2/1 - 5Y2/1) calcareous shales (5-200 cm thick), and marly biocalcilutites (8-100 cm thick). At the field-scale, the sequence is monotonous and contains only scarce inoceramids and few ammonites, and both types of rocks reveal the presence of continuous and persistent 1-2 mm thick fine laminae (Fig. 5 A). At the microscopic scale, petrographic studies of the thin sections reveal that laminae are formed by intercalation of even-parallel to wavy-parallel, light and dark sub-units that resemble varve deposits. Light laminae are mainly composed of calcite-filled "micro-ooids" or "microspheres" between 5 and 100 μm with a median size of 40 μm (Fig. 5 B, C). These granular components are less abundant in the dark laminae that also include few scattered planktonic foraminifera, and scarce radiolarians. In addition to the microspheres, the main components of the matrix include 30 to 50% undifferentiated clay-size particles, up to 5% scattered framboidal pyrite aggregates, and microsparite is the main cement, although macrosparite is found in microfractures.

Microscopic observations also reveal that the conspicuous laminae observed at the macroscopic scale are in fact not continuous; they occur as uneven discrete units with pinch and swell structures. The types of structures associated with the "microspheres" are similar to those shown by Kazmierczak and Kempe (1992), Kazmierczak *et al.* (1996), Tribovillard (1998), Kazmierczak and Altermann (2002), and Tribovillard *et al.* (2000) that have been interpreted to be of bacterial origin.

4.2. Scanning Electron Microscope (SEM) descriptions

Backscatter and secondary electron imaging of samples from Parras de la Fuente corroborate and further define the microstructures observed in the petrographic analyses. As stated previously, lamination does not occur in samples of either Las Delicias or the La Casita sites. The shales and biocalcilutites from the Parras area are predominately composed of distinct microspheres that are consistently spherical, semi-spherical and ovoid in shapes (Fig. 6 H - M). They occur as scattered individuals, and in aggregate strings of microspheres (Fig. 6 B, F). Most of the microspheres regularly exhibit a 3 to 5 µm-thick rim of microcrystalline calcite reminiscent of a "test". Microspheres are made up of single or multiple crystals of sparry calcite aggregates that are analogous to the internal structures of strings of attached cells described by Gobulic and Campbell (1981), and to cell-like structures (Kazmierczak and Krumbein, 1983; Kazmierczak and Altermann, 2002) interpreted to be the result of the calcification of living cyanobacteria. Some of these strings may resemble heterohelicid planktonic foraminifera in edge view, but we rule out this possibility because the shell structure is different, and it is unlikely that biserial foraminifers would consistently orientate in such a way as to have only the edge view exhibited in both SEM and petrographic images.

SEM semi-quantitative EDS analyses of samples from Parras de la Fuente and Canyon la Casita supports the petrographic observation of a high clay content of these sites. Data for the Canyon la Casita shows a high silica and aluminum content in the matrix (Fig. 7). The observed pattern is characteristic of minerals of clastic origin and most probably of the clay group, consistent with the EDS analysis of high silica and aluminum. The matrix at Parras de la Fuente is composed mainly of microcrystalline calcite and minor amounts of framboidal pyrite (Fig. 8).

4.3. Carbon/Carbonate analysis

Samples from the three sections where analyzed for their relative percentages of organic and inorganic carbon, and the results are presented as percentage (%) of total dry weight of the bulk sample (Table 1). The data clearly show strong and marked differences in the carbon/carbonate contents between the three areas (Fig. 9).

Results from Las Delicias (stratotype area) yield carbonate percentages that vary between 48 and 90%, and

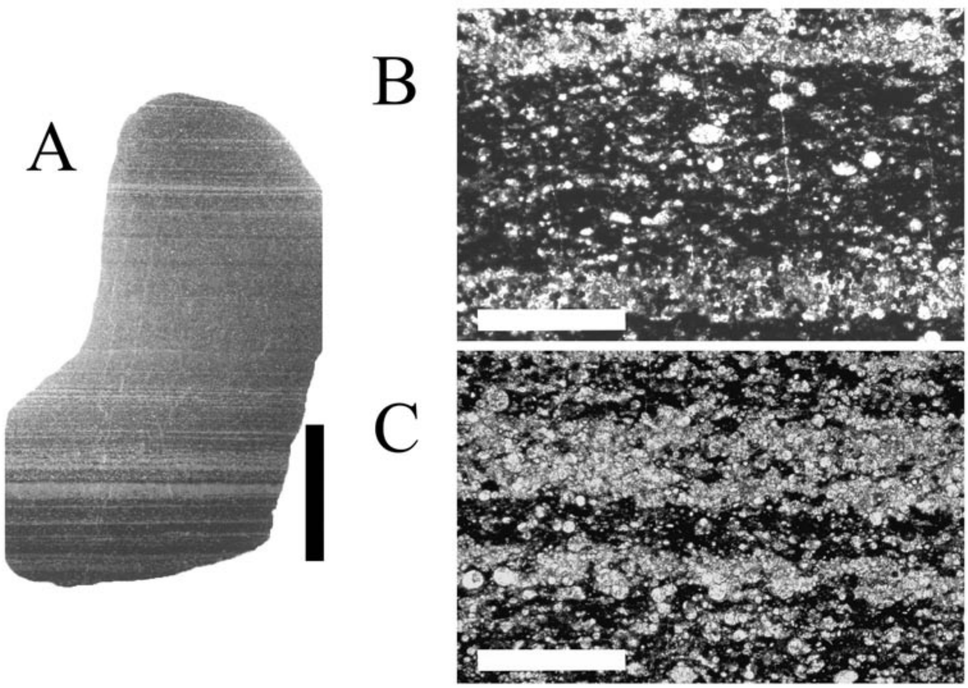

Fig. 5.- A) Petrographic thin section from Parras area: conspicuous parallel laminations clearly form couplets that resemble 'varves'. Laminae are even-parallel and are classified as very thin laminae <3 mm (scale bar = 1.5 cm). B and C) Biocalcilutite microphotographs (plain light), laminations at this magnification when compared with the macro level are not continuous, but instead they form a wavy pattern that is characterized by lower to higher concentration of 'microspheres' (B and C scale bar = 500 µm).

Fig. 5.- A) Lámina delgada de una muestra de Parras: laminación paralela conspicua semejante a "varvas". Las laminillas son continuas y paralelas, y son clasificadas como laminillas muy finas <3 mm (Escala gráfica= 1,5 cm). B y C) Fotomicrografias de biocalcilutitas (luz natural); a este aumento y en comparación con su apariencia macroscópica, las laminaciones son discontinuas, formando un patron ondulante caracterizado por mayores o menores concentraciones de "microesferas" (Escala gráfica en B y C = 500 µm).

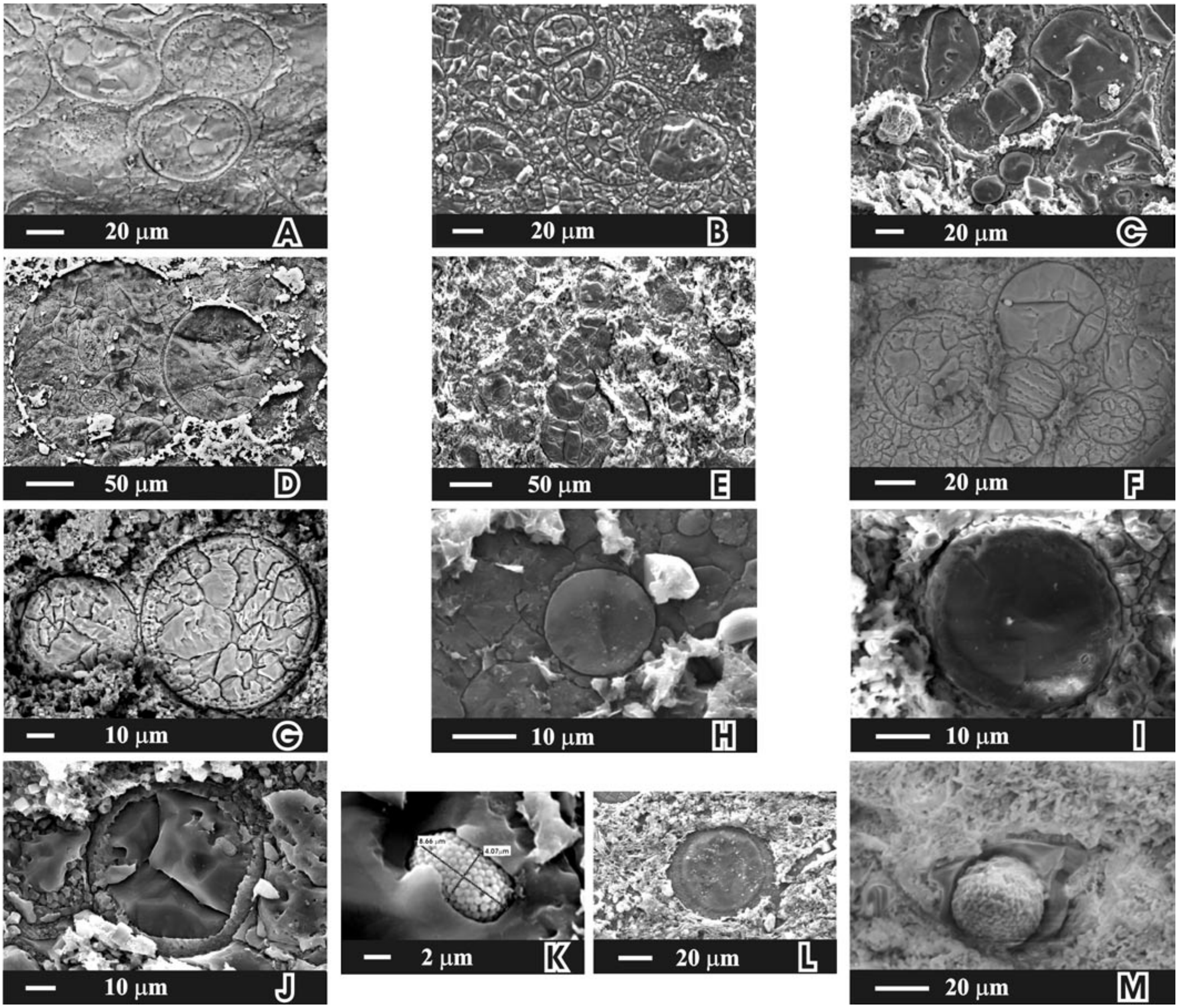

Fig. 6.- Scaning Electon Microscope images. High magnification allows us to show that microspheres have spherical (A, C, D, G, H, I, J, L), semispherical and ovoid shapes (B, C, E), and consistently exhibit a 3 to 5 µm rim of microcrystalline calcite that is reminiscent of a test. Microspheres are made up of single (C, H, I, L) or multiple crystals of sparry calcite (A, B, D, E, F, G, J) and are found isolated (H, I, J, L) or as aggregates that resemble strings of attached cells (A, B, C, D, E, F, G). K and M are pyrite framboids. K is a close up of a pyrite framboid found inside L (arrow), and M is a framboid in the matrix.

Fig. 6.- Imágenes de Microscopio Electrónico de Barrido (SEM). El gran aumento permite ver las diferentes formas de las microesferas: completamente esféricas (A, C, D, G, H, I, J, L), semiesféricas y ovoidales (B, C, E); las cuales muestran, consisténtemente, un anillo de 3 a 5 µm de calcita microcristalina que sugiere una conchilla. Las microesferas están constituidas por un solo cristal (C, H, I, L) o por múltiples cristales de esparita (A, B, D, E, F, G, J), hallándose aisladas (H, I, J, L) o como agregados que aparentan ser células encadenadas (A, B, C, D, E, F, G). K y M son framboides de pirita. K es un detalle de un framboide de pirita encontrado dentro de L (flecha), y M es un framboide dentro de la matriz.

TOC between 0.73 and 1.9 %, while the non-carbonate fraction ranges from 4.5 to 50%. These values are consistent with the petrographic observation of high carbonate content. Relatively low TOC is also in agreement with our previous inference of a well-oxygenated bottom that not only sustained a rich benthic fauna that homogenized the sediments, but also caused oxidation of organic matter and enhanced microbial degradation (Andersen and Kristensen 1992).

Results from Canyon la Casita yield carbonate percentages that vary between 0.8 and 59.3%, and TOC between 0.1 to 5.8%, but most consistently below 2%. As deduced from the TC values shown in Table 1, the non-carbonate fraction ranges from 34.8 to 98.9%. Since TOC values vary independently from total non-carbonate fraction, they imply that the influx of terrigenous supply did not control the preservation of the organic matter (Canfield, 1992). Although total carbonate has been affected by diagenesis, as shown by the calcitized radiolarian tests, TOC values being weakly covariant with the carbonate content suggest that the triggering factors that controlled carbonate producers also affected the total biomass production that caused enhanced organic carbon accumulation and/or preservation.

Results from Parras de la Fuente area yield high carbonate percentages with values varying between 43% and 78.3%, a much higher range than those observed at Canyon la Casita, but within the range of values observed at Las Delicias. TOC values are also the highest out of the three areas, with values between 7.3 and 24.9%, and commonly higher than 20%. The non-carbonate fraction varies between 4.7 and 34.6% (Fig. 9, Table 1), and independently from the TOC values, as discussed for the site at la Casita. The high TOC values coincide with sedimentary facies with minimum bioturbation, and therefore where laminae and original fabric are preserved.

5. Discussion and Conclusions

Assuming coevality of the facies between the different sites at Las Delicias (type area), Canyon la Casita and Parras de la Fuente, their high variability in sediment type, faunal content and TOC, underscores non-uniform environmental conditions over the Mexican Platform.

Comparison of the TOC values versus all other constituents from the areas studied shows great variation in the $C_{organic}$ contents (7.3% to 24.9% at Parras) that can be interpreted to be the result of differences in oxygenation level, productivity and preservation of the organic matter. Based on the macrofaunal composition of the facies that occurs at Las Delicias, it is evident that waters at that site remained more oxygenated. Thus, the lower TOC values (0.73 – 1.9 %) in that area may be indicative of higher oxic level and faster degradation of organic matter that

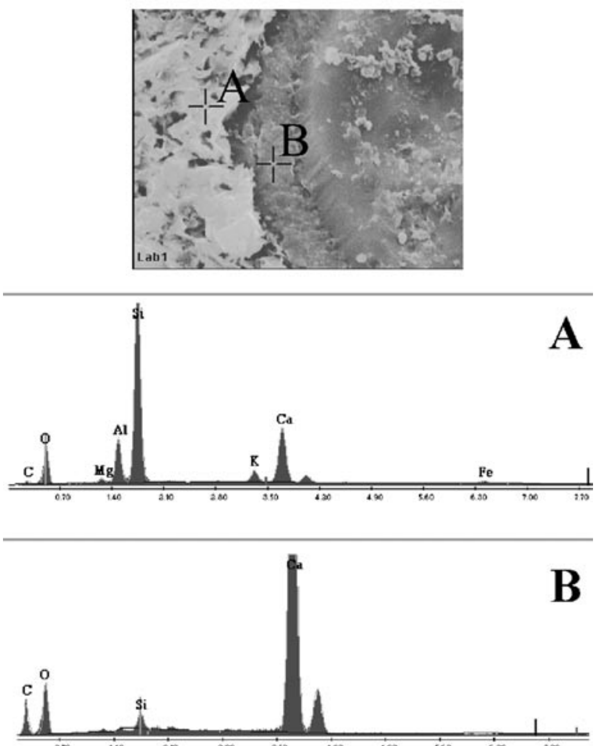

Fig. 7.- SEM-EDS image and semiquantitative chemical analysis from Parras de la Fuente. Matrix (A) analysis shows higher abundance of silica, aluminum, potassium and iron when compared to 'microspheres' (B).

Fig. 7.- Imagen SEM-EDS y análisis químico semicuantitativo de Parras de la Fuente. El análisis en la matriz (A) muestra abundancias grandes de sílice, aluminio, potasio y hierro respecto a las encontradas en las 'microesferas' (B).

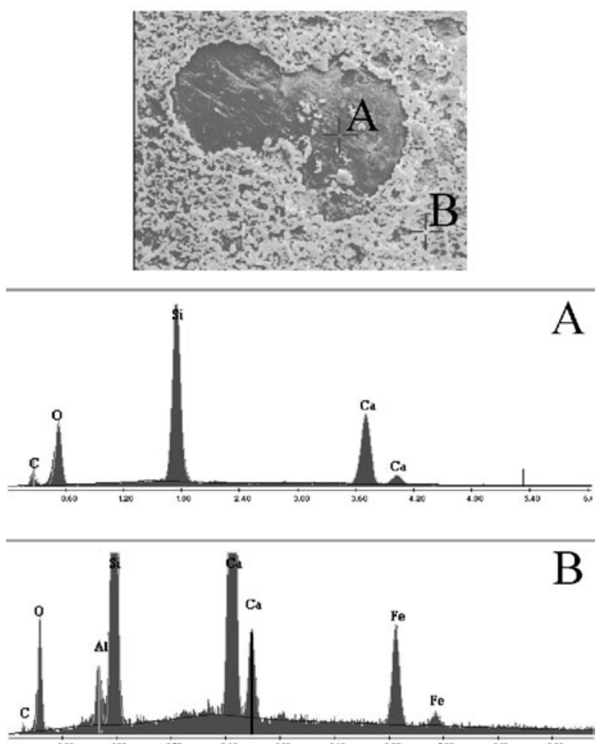

Fig. 8.- SEM-EDS image from Canyon la Casita. Foramifer (A) analysis shows high abundance of silica indicating silicification. Matrix (B) shows silica, aluminum and iron being abundant in the matrix; the latter two are not present inside microfossils.

Fig. 8.- Imagen SEM-EDS del Cañon La Casita. El análisis de foraminíferos (A) muestra un alto contenido de sílice, producto de una silicilificación. La matriz (B) presenta sílice, aluminio y hierro, los cuales son abundantes en la matriz; los dos últimos no están presentes en los microfósiles.

	Sample	Total Carbon (wt%)	Total Carbonate (wt% $CaCO_3$)	TOC (wt%)
Parras de la Fuente	**MXF-1**	27.40	43.08	22.23
	MXF-2A	15.95	71.55	7.36
	MXF-2C	26.18	44.60	20.83
	MXF-3	21.55	65.90	13.64
	MXF-4A	22.78	78.29	13.38
	MXF-4B	21.27	69.92	12.88
	MXF-5	29.95	46.32	24.39
	MXF-6	25.41	69.82	17.03
	MXF-7	25.73	65.96	17.81
	MXF-8	30.30	73.80	21.44
	MXF-N-14	27.64	73.48	18.82
	MXF-N-15	26.19	63.16	18.61
	MXF-N-16	26.64	49.94	20.65
	MXF-N-18	29.68	57.87	22.74
Canyon La Casita	**MXF-N-1**	7.98	51.97	1.74
	MXF-N-2	4.73	26.04	1.61
	MXF-N-3	4.94	15.69	3.06
	MXF-N-4	0.28	0.84	0.18
	MXF-N-5	1.95	9.37	0.83
	MXF-N-7	6.11	36.63	1.71
	MXF-N-8	4.70	30.74	1.01
	MXF-N-9	4.74	25.00	1.74
	MXF-N-10	3.02	17.61	0.91
	MXF-N-11	5.87	30.73	2.18
	MXF-N-12	12.98	59.31	5.86
	MXF-N-13	5.13	37.38	0.64
Las Delicias	**MXF-N-20**	10.30	78.89	0.83
	MXF-N-21	7.68	48.08	1.91
	MXF-N-24	12.98	93.74	1.73
	MXF-N-25	11.39	88.73	0.74
	MXF-N-26	12.51	90.97	1.59

Table 1.- Carbon analysis values are expressed as carbon percent C (%) for dry weight bulk sample, except in the central column where carbonate percentages of each sample are indicated (TOC=Total organic carbon).
Tabla 1.- Los valores de los análisis están expresados en porcentajes de C (%) del peso en seco de la muestra, excepto en la columna central donde se indican los porcentajes de carbonato en cada muestra (TOC = Carbono orgánico total).

may have been produced. Although we cannot preclude that organic production was effectively lower, conditions conducive to degradation of organic matter may have been further enhanced by metazoan benthos bioturbation, which can stimulate microbially mediated decomposition reactions (Andersen and Kristensen, 1992).

The sedimentary sequence studied at Parras has been commonly assigned to the Indidura Formation, but our study provides further evidence to corroborate previous suggestions (Imlay, 1938) that lateral correlation with the stratotype at La Delicias remains unclear because the two types of facies are quite different. In fact, their lateral continuity is undocumented in either area, and this issue was raised by Imlay (1938, p. 1692) who noted that "… Comparing the highly fossiliferous Indidura formation in central Coahuila with the un-fossiliferous so-called Indidura formation in areas off-shore from the Coahuila Peninsula, the question arises as to whether they should be recognized by the same name." This discrepancy between the facies is further supported by the results of our work showing that various parameters such as field-scale observable rock characteristics, microfacies, as well as organic carbon, and carbonate contents show fundamental dissimilarities usually associated with lithostratigraphic units of next higher rank to formation (NACSN, 1983). Thus, as compared to the type area, usage of the term "Indidura Formation" in the Parras Mountains is for practical purpose, and is therefore in a broad sense (*sensu lato*) based on precedence, until the issue is further addressed in our ongoing investigation. By analogy with structures previously reported to be bacterially generated, microgranules that make up the main constituents of the laminae in the sequence at Parras are interpreted to represent deposits produced by bacterial activities that accumulated as bacterial mats. In fact, the laminae are identical to sedimentary laminae described by Schieber (1986), O'Brien and Slatt (1990) and O'Brien (1996) in Paleozoic shales, and associated rocks. The presence of very few inoceramids, the absence of other benthic organisms, and low level of bioturbation throughout the sequence at the Parras site are corroborative evidence that dysoxic to anoxic bottom water prevailed within the time interval studied. Differences between the sites are interpreted to be related to paleogeophysiographic irregularities of the Mexican Platform, and associated differences in paleoceanographic conditions that controlled variabilities in the sedimentary record.

In fact, sedimentary and fossil structures similar to those identified in the Parras sediments can be equated to fossilized counterparts of present cyanobacterial and microbial communities (Tribovillard, 1998; Tribovillard *et al.*, 2000). Similarly, differential accumulation rates of the bacterial masses gave rise to pinch and swell structures (Schieber, 1986). The scarcity or consistent absence of both planktonic and benthic fauna also indicates competitive exclusion caused by perennial dominance of bacterial colonies throughout the water column.

Perhaps, in addition to special local physiographic factors inherent to the Mexican Platform, upward flux of nutrients that sustained high cyanobacterial productivity for such extended period may have been influenced

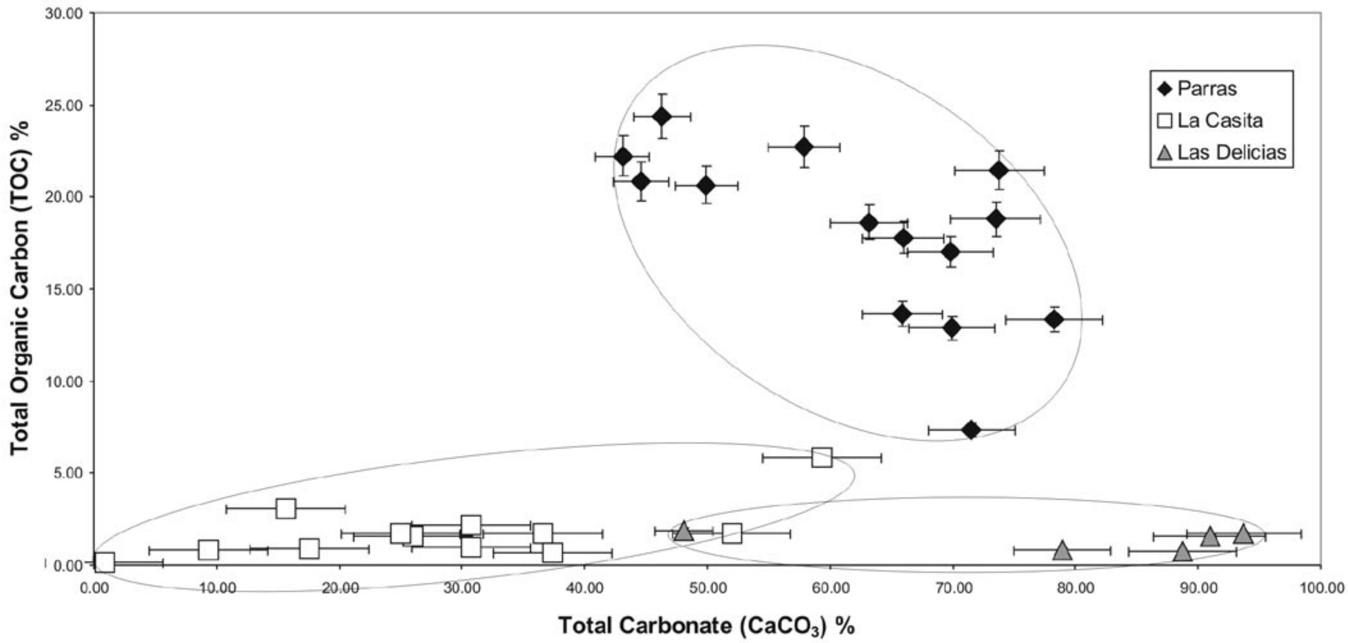

Fig. 9.- Total Organic Carbon (TOC) and Total Carbonate ($CaCO_3$) contents. Samples from the three sections show distinct proportions indicating that environmental conditions greatly differed over the accumulation area. High TOC values correlate with low bioturbation as see in Figure 5, while lower values are associated with distorted primary sedimentary structures and burrowing (Figs. 3 and 4) .

Fig. 9.- Contenidos de Carbono Orgánico Total (TOC) y Carbonato Total ($CaCO_3$). Las muestras de las tres secciones tienen proporciones distintas indicando que las condiciones ambientales difirieron ampliamente a través del área de acumulación. Los altos contenidos de TOC se corresponden con bajas bioturbaciones, tal como se ve en la Figura 5, mientras que los valores bajos están asociados con estructuras primarias distorsionadas y madrigueras (Figs. 3 y 4).

by global forcing factors associated with the overall warm and equable climates that prevailed at these times. Warmer global temperatures would certainly increase evaporation, and given the proper regional physiographic conditions would consequently induce generation of thermohaline warm saline bottom water (WSBW), which in turn increased upwelling. Such mechanism can enhance higher productivity, and maximize the storage of mass quantities of organic matter in worldwide events (Jenkyns *et al.,* 1994; Norris *et al*., 2001).

We conclude that close analogs to such microbial production are those of planktonic blooms of calcifying cyanobacteria (Robins and Blackwelder, 1992; Robins *et al.,* 1997; Yates and Robins 1998, 2001), and non-calcifying cyanobacteria (Carpenter and Romans, 1976; Carpenter, 1983) reported as common occurrences in present oceans. In the Indian Ocean, for instance, differences in stratification of the near-surface waters caused by the monsoon periods control the alternance of nitrate-limited cyanobacterial blooms versus normal phytoplankton productivity (Devassy *et al*., 1978; Sen Gupta and Naqvi, 1984). When phytoplanktons are able to thrive they limit bacterial colonies, which then become more dispersed. We believe that a similar cyclic production of picoplankters may explain the presence of dark laminae 'cyanobacterial rich' (anoxic conditions) and light laminae 'cyanobacterial poor' (dysoxic conditions). In addition, unusually high bacterial productivity may explain enhanced oxygen depletion recorded in the depositional environment of the Parras area, where relatively low-oxygen concentrations that existed in the "Mid" Cretaceous oceans (Tatsumi *et al.* 1998) would further exacerbate the conditions in that area as compared to the other sites.

Another factor to consider is the possible role played by iron in these environments, as experiments by Coale *et al.* (1996) have demonstrated that primary productivity can be highly affected by the introduction of even small quantities of Fe into the upper water column, causing oceanic phytoplankton blooms. The pattern of TOC fluctuation in the area studied suggests that a similar influence may have played an important role during the accumulation of the $C_{organic}$-rich sediments on the northeastern Mexican basin at that time. Several scenarios can be considered to provide likely sources for Fe, *e.g.* wind-blown particles, enhanced hydrothermal activity, and riverine input. We believe that a wind-blown provenance is less likely, because of the limited areal extent of deserts during the Cretaceous, as attest only few occurrences of eolian deposits (China, Canada, Africa and Brazil). Such record is compatible with expected global response to warm and equable climates during "green house conditions" (Loope *et al*., 1998; Bird, 1984).

Enhanced hydrothermal activity can be a relevant factor at that time, which corresponds to increased sea floor spreading activity, as well as emplacement of the latest stages of Large Igneous Provinces (LIP's) such as the Ontong Java and Caribbean plateaus (Sinton and Duncan, 1997; Kerr, 1998). Thus, increasing flux of iron in the ocean waters may have permitted large-scale phytoplankton blooms in areas where Fe acted as a biolimiting nutrient. In such cases, intensified supply of organic matters and decomposition through the water column would also intensify oxygen consumption, hence reducing available O_2, conditions that will be optimum for generation of Corg-rich deposits. Although this is a likely process that may have contributed to the cyanobacterial blooms, it does not explain the cyclical lamination and larger-scale interbeds observed in the Indidura Formation (*s.l*).

Riverine input that may reflect a seasonal component seems the most likely triggering mechanism to explain the high frequency of changes recorded by the laminae. As observed in present environments, periodic influx of fresh water rich in clays, dissolved iron and other nutrients, could have induced conditions in the "Mid Cretaceous" where cyanobacteria were able to thrive almost at the exclusion of all other organisms. In particular, the situation of the basin associated with the facies at Parras would have been comparable to patterns of riverine iron influx and its critical role in the accumulation of sapropels in the Mediterranean Sea. In the latter case, the pattern fluctuated as the head and catchments areas of the Nile shifted due to changes in the position of the Intertropical Convergence Zone (Krom *et al.*, 2002). By analogy, paleogeographic conditions in the Gulf of Mexico/ Northeastern Mexico region may have been conducive to similar periodic incursions of iron-rich or iron-poor riverine waters in the existing basin associated with the Mexican Platform. In combination with a fortuitous nitrogen limitation, these fluctuating iron supplies could have created favorable conditions for periodically enhanced cyanobacterial blooms that produced high concentrations of Corg-rich detritus. Consequently, low dissolved O_2 further allowed alternating accumulation of $C_{organic}$-rich sediments in a recurrent mode that generated the sedimentary features, or varve-like laminae and beds couplets observed in the succession of the Indidura Formation (s.l) at Parras.

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